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Experimental Demonstration of All-Optical 781.25-Mb/s Binary Phase-Coded UWB Signal Generation and Transmission

Xianbin Yu, Timothy Braidwood Gibbon, and Idelfonso Tafur Monroy

***Abstract*—In this letter, an all-optical incoherent scheme for generation of binary phase-coded ultra-wideband (UWB) impulse radio signals is proposed. The generated UWB pulses utilize relaxation oscillations of an optically injected distributed feedback laser that are binary phase encoded (0 and π) and meet the requirements of Federal Communications Commission regulations. We experimentally demonstrated a 781.25-Mb/s UWB-over-fiber transmission system. A digital-signal-processing-based receiver is employed to calculate the bit-error rate. Our proposed system has potential application in future high-speed UWB impulse radio over optical fiber access networks.**

***Index Terms*—Binary phase-shift keying (BPSK), digital signal processing (DSP), impulse radio, optical generation, ultra-wideband (UWB), UWB-over-fiber.**

I. Introduction

ULTRA-WIDEBAND (UWB) systems specified by the Federal Communications Commission (FCC) can provide large bandwidth under unlicensed spectrum (3.1–10.6 GHz), support high bit rate and extremely low radiation power, and operate at very low signal-to-noise ratio (SNR) [1]. However, the tradeoff between UWB Shannon's channel capacity and propagation distance, and the specifications of the FCC limit that UWB is only a promising technology for short-range communication applications. Similarly, to the well-known advantages of radio-over-fiber systems [2], UWB-over-fiber technology is capable of extending the access distance and subsequently distributing wireless signals to end users. Therefore, UWB-over-fiber technology is very attractive.

In UWB-over-fiber systems, a key issue is how to generate FCC compliant UWB signals in the central office with cost-efficient and low-complexity photonic components commonly used in optical fiber access systems. Recently, some approaches have been proposed and demonstrated to optically generate ON–OFF keying (OOK) modulated UWB pulses [3]–[8]. For example, an OOK return-to-zero (RZ) pulse generator has been demonstrated in [7] by using fiber-grating-based pulse shaper. However, phase-modulated signals give extra 3 dB in SNR for any given noise level, and are therefore of special interest for UWB-over-fiber systems. Therefore, optical generation

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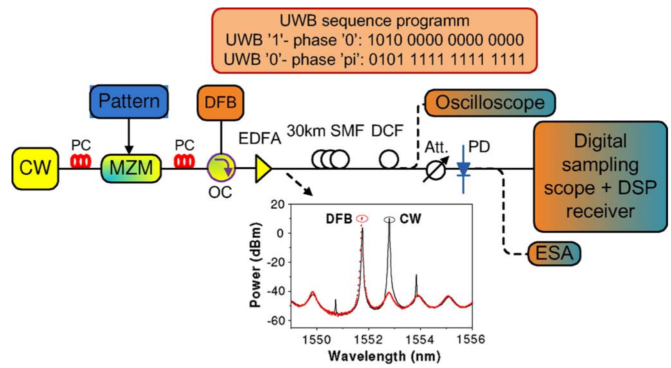


Fig. 1. Schematic configuration for the generation of binary phase-coded UWB pulses. CW: continuous-wave laser; MZM: Mach-Zenhder modulator; PC: polarization controller; DFB: distributed feedback laser; OC: optical circulator; EDFA: erbium-doped fiber amplifier; OSA: optical spectrum analyzer; SMF: single-mode fiber; DCF: dispersion compensation fiber; Att.: attenuator; PD: photodiode; and ESA: electrical spectrum analyzer.

of phase-modulated UWB signals is highly desirable. Several schemes have been proposed for generating biphase-modulated signals by using optical pulse shaping (optical filter or fiber Bragg grating) and multilaser sources [9], [10], or an external optical modulator array [11].

In this letter, we proposed an incoherent scheme to optically generate binary phase-shift keying (BPSK)-modulated UWB signals. The proposed method is based on the relaxation oscillations of a distributed feedback (DFB) laser and incoherent optical field summation of an input optical signal and the corresponding output signal of an externally injected DFB source [12]. Moreover, we experimentally demonstrate a 781.25-Mb/s BPSK-UWB transmission system based on the incoherent method. A digital-signal-processing (DSP)-based receiver is employed to evaluate the transmission bit-error-rate (BER) performance.

II. Experiment Setup and Operation Principle

The experimental setup is shown in Fig. 1. A continuous wave (CW) from a tunable laser is polarization-controlled and launched into a Mach–Zehnder modulator (MZM), which is driven by a sequence of 12.5-Gb/s electrical pulse pattern. The output optical signal of the MZM is then injected into a DFB operating at a peak wavelength of 1551.48 nm. Since the current-used DFB is polarization dependent, another polarization controller (PC) is used to adjust the polarization states. An optical circulator (OC) is used to forward the output signals from DFB to the transmission link, which consists of 30-km single-mode fiber (SMF) and 5-km-matched dispersion compensation

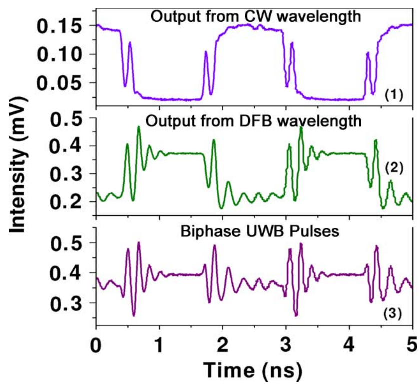


Fig. 2. (1) Output pattern from CW wavelength; (2) output pattern from DFB wavelength; (3) calculated biphase UWB pulses by combining the measured signals of (1) and (2).

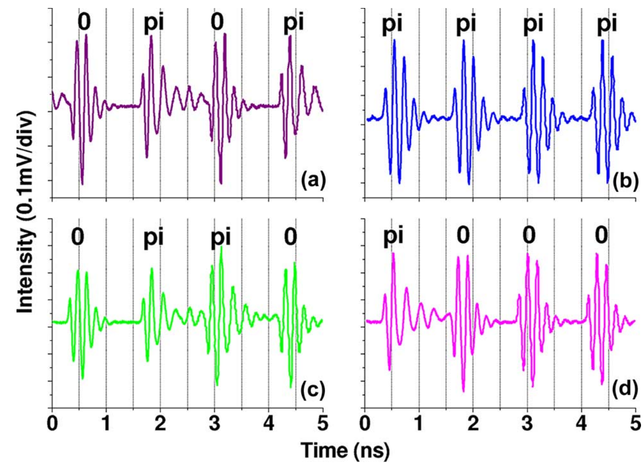
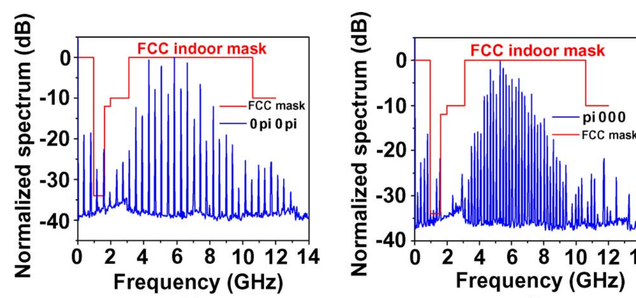


Fig. 3. Generated 4-bit BPSK-coded pulses in time domain with phase sequences. (a) $0\ \pi\ 0\ \pi$. (b) $\pi\ \pi\ \pi\ \pi$. (c) $0\ \pi\ \pi\ 0$. (d) $\pi\ 0\ 0\ 0$.



(a) (b)

Fig. 4. Frequency spectra of the generated UWB signals with phase sequences: (a) $0\ \pi\ 0\ \pi$ and (b) $\pi\ 0\ 0\ 0$.

fiber (DCF). An erbium-doped fiber amplifier (EDFA) is used to compensate the loss of SMF and DCF. An optical spectrum analyzer (OSA) is employed to observe the signals in the optical domain. The resultant electrical signal after the high-speed photodiode (PD) is analyzed by using an electrical spectrum analyzer (ESA) in the frequency domain, and an oscilloscope (Agilent Infiniium 86100 A wide bandwidth oscilloscope) with 20-GHz bandwidth in the time domain. At the receiver side, a high-speed sampling scope at 40 Gsample/s is used to receive the signals.

To enhance the cross-gain modulation (XGM) interaction between the CW and DFB emitting wavelength [5], the injection wavelength is chosen to be 1552.56 nm, which is located at the DFB first-order side mode. The optical spectra are shown in Fig. 1 (inset). When the DFB is modulated by a binary bit stream and biased above laser threshold for digital zero level, due to the relaxation oscillations, a transient overshoot beyond the steady state takes place for input bit 1 and an undershoot for an input bit 0. As shown in Fig. 2, when 32-bit 12.5-Gb/s patterns of the form ''1010 0000 0000 0000'' and ''0101 1111 1111 1111'' are used to drive the MZM, the overshoot and undershoot at the output of the DFB can be observed in Fig. 2(2). An optical bandpass filter with 0.4 nm bandwidth is used to load these two wavelengths one by one and measure, see Fig. 2 [(1)and (2)]. XGM introduces a π phase difference between the input signal (CW wavelength) and DFB output signals. This relative π phase difference between the two 16-bit input patterns contributes to the phase of the generated pulses after photodetection. Therefore, the incoherent summation of these two optical signals generates biphase-coded pulses with complex waveforms. The calculated pulses are displayed in Fig. 2(3) by combining the outputs from these two wavelengths. We can note that assuming the pattern ''1010 0000 0000 0000'' generates 0 phaseshift, then the pattern ''0101 1111 1111 1111'' generates a π phaseshift, and BPSK-UWB pulses are created in this way.

III. Experimental Results and Discussion

The experimental results measured from the oscilloscope are shown in Fig. 3. A 64-bit 12.5-Gb/s pattern is used to generate UWB pulses with relatively π out of phase for illustration purposes. The pulses in Fig. 3(a) validate the simulated $0\ \pi\ 0\ \pi$ phase sequence in Fig. 2(3) and the principle discussed before. Moreover, by programming different combinations of input patterns, different optical pulses, and hence, different phase-coded UWB sequences can be obtained. An example of the generated 4-bit UWB signals with phase sequences $\pi\ \pi\ \pi\ \pi$, $0\ \pi\ \pi\ 0$, and $\pi\ 0\ 0\ 0$ are shown in Fig. 3(b)–(d). We can observe that there are different intensity levels for UWB pulses with ''π'' phase code and ''0'' phase code. This is because the overshoot level for the input bit ''1'' is higher than the undershoot level for the input bit ''0'' in the DFB. Meanwhile, an ESA is used to measure the generated signals in the RF domain. The results are shown in Fig. 4, as well as the FCC mask. Both cases of $0\ \pi\ 0\ \pi$ and $\pi\ 0\ 0\ 0$ sequences are displayed. They indicate that the generated signals in the frequency domain fit well within the FCC mask.

In the transmission experiment, a long 12.5-Gb/s input pattern is programmed, resulting in a 781.25-Mb/s BPSK-UWB $2^7 - 1$ pseudorandom bit sequence (PRBS). The frequency spectra with PRBS before and after fiber transmission are displayed in Fig. 5. We can observe that the transmission does not change the frequency spectra. Although the generated signals after transmission satisfy the FCC emission mask, our presented analysis is restricted to the fiber transmission part, and it requires a further air link propagation analysis to be complete. For the reception, the signals are sampled at 40 Gsample/s (Agilent Infiniium DSO80000B with 13-GHz analog bandwidth), and then processed offline. DSP receiver is based on correlation, adaptive threshold, and bit-for-bit comparison. Fig. 6 displays the sampled ''1 0 1 0'' 4-bit UWB

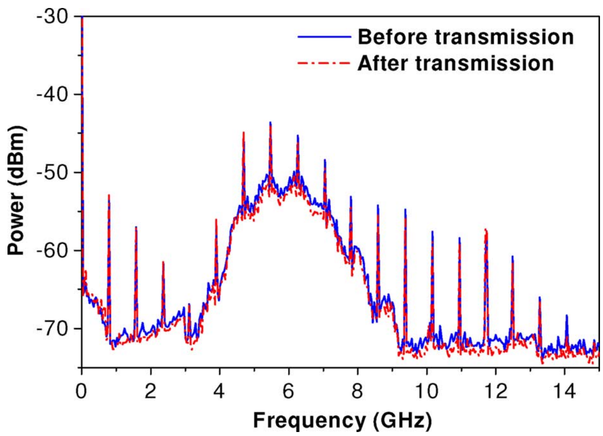


Fig. 5. Frequency spectra before and after transmission when a $2^7 - 1$ PRBS pattern is applied.

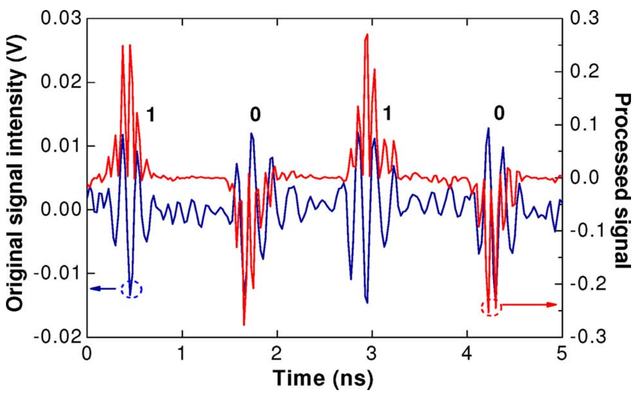


Fig. 6. Sampled and DSP processed ''1 0 1 0'' 4-bit UWB signals.

signals. In the DSP domain, each UWB bit is first separated and normalized, and then, correlated with a normalized mask bit. Subsequently, the logical value of each UWB bit is determined by comparing the sum of the processed signal points within each bit slot to an optimally determined decision threshold. Finally, a bit-for-bit comparison between the transmitted and received bits is used to calculate the BER. The deviations from the expected 0 or π phaseshift will result to detection performance degradation depending on its values and DSP receiver structure. Fig. 7 shows the BER results for 1.9×10^5 sampled UWB bits. There is insignificant penalty between back-to-back and 30 km transmission link, and no error bits were detected at a receiver power of -12.5 dBm.

IV. Conclusion

We proposed an all-optical biphase pulse modulation scheme for UWB-over-fiber communication systems. The proposed method is based on incoherent summation of an intensity-modulated signals that is used to externally inject a DFB laser and the relaxation oscillations of the DFB laser. In particular, our scheme is filter free. The experimental results indicate that the generated UWB signals are binary phase encoded (0 and π) in the time domain and compliant with the FCC spectral mask. Furthermore, we demonstrate a 781.25-Mb/s BPSK-UWB transmission system. A bit-for-bit comparison

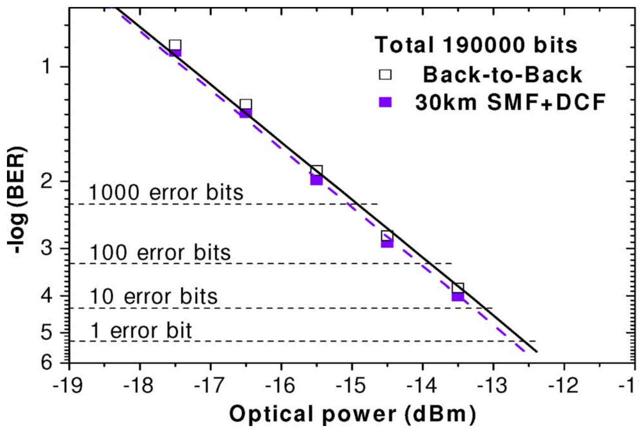


Fig. 7. UWB BER curves for back-to-back and transmission. In this case, a bit-for-bit comparison and 1.9×10^5 UWB bits are used to calculate BER.

and DSP-based receiver are used to calculate the BER performance. The BER results show that the 30 km SMF transmission does not introduce penalty and no error bits were detected at -12.5 dBm. Our proposed system shows potential application in future high-speed UWB impulse radio over optical fiber access network.

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